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SENSITIVITY ANALYSIS ON THE M60A1E2 TURRET STABILIZATION WITH DIFFERENTIAL PRESSURE FEEDBACK

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ABSTRACT

It has been demonstrated by performance evaluations on M60A1E2 tanks and by the results of simulator studies that the dynamic accuracy of the M60A1E2 turret azimuth stabilization system can be greatly improved with a minimum change in existing hardware. This change is the replacement of the derived acceleration compensation term in the control system by feedback of the differential pressure across the traverse motor. With this modification there is no longer a need to tune each stabilization system to an individual tank. and all control gains would be fixed prior to installation of the system into the tank.

A sensitivity analysis was performed on the modified stabilization system so that the effect of tank and stabilization system unit-to-unit and environmental parameter variations could be assessed. This study was performed with the aid of the analog simulation of the turret-hull azimuth model as determined by measurements taken on the MICOM tank. This report also describes the criteria used for evaluating stabilization system performance and the reasoning behind the statistics utilized to describe the parameter variations considered.

The sensitivity analysis showed that only one of the 27 error sources considered had a serious effect on the dynamic accuracy of the turret azimuth stabilization system. However, this error source, hull gyro channel gain, caused the turret hangoff during simulated cross-country aim retention to be only slightly out of the specification tolerance, and this error source has a much more degrading effect on the original system. There was no indication that any of the parameter variations would keep the turret azimuth stabilization system from meeting the specifications for laying on stationary and moving targets.

The modified system has demonstrated that it effectively overcomes the dynamic accuracy problems of the original system and is much less sensitive to parameter variations.

CONTENTS

ILLUSTRATIONS

SYMBOLS

B	turret-to-hull viscous friction coefficient (ft-lb/rad/sec)
B_B	basket-to-turret viscous friction coefficient (ft-lb/rad/sec)
B_C	turret-to-hull coulomb friction coefficient (ft-lb)
B_g	geartrain-to-turret viscous friction coefficient referenced to turret (ft-lb/rad/sec)
B_{cg}	geartrain-to-turret coulomb friction coefficient referenced to turret (ft-lb)
B_H	vehicle suspension viscous friction coefficient (ft-lb/rad/sec)
J_e	equivalent gear moment of inertia referenced to turret (slug-ft^2)
J_h	hull plus stabilized turret moment of inertia (slug-ft^2)
J_t	turret plus locked cupola moment of inertia (slug-ft^2)
K	traverse motor gain constant
K_f	spring constant equivalent of fluid compliance referenced to turret (ft-lb/rad)
K_g	spring constant of geartrain sturcture referenced to turret (ft-lb/rad)
K_h	spring constant of vehicle suspension (ft-lb/rad)
K_P	gain associated with turret position (mA/rad)
K_P'	position loop gain through control system, vehicle, and sensors
K_V	gain associated with turret velocity (mA/rad/sec)
K_V'	velocity loop gain through control system, vehicle, and sensors
K_{HS}	hull sync gain (mA/in.)
$K_{\Delta P}$	differential pressure feedback gain (mA/psid)
T_s	stall torque (ft-lb)

Section I. INTRODUCTION

When Army Missile Command (MICOM) was brought into the M60A1E2 program there were two primary problems with the stabilized turret: system dynamic performance and accuracy, and component reliability. Although the (MICOM) effort was centered on the first problem, there was some natural fall-out that affected the second problem.

The basic dynamic performance and accuracy problem was that if the loop gains were sufficiently high to give the desired aiming accuracy with external disturbance inputs and to give relatively low sensitivity to tank and control system parameter variations then the stabilization system would be unstable. In order to overcome this effect and to meet acceptance tests, each stabilization system had to be tuned for the individual tank and for the particular acceptance test being performed. In addition, the tuning procedure is difficult and extremely dependent upon the individual doing the tuning. The MICOM tank was tuned several times by both Cadillac Gage and Chrysler personnel, and a wide variation in system performance and gain settings resulted.

There is also a coupling between the system performance and component reliability problems. Since the original M60A1E2 stabilization system is so critical to system parameter values that each stabilization system must be tuned to the individual tank, any changes in these parameters due to age and environment will cause severe degradation of stabilization system performance. Therefore a system which is relatively insensitive to parameter variations would be more tolerant of component changes that would cause the original system to become inoperative or severely degraded. Thus, a system with less parameter sensitivity should be more reliable.

The turret azimuth stabilization loop was chosen for the MICOM study. An analog simulation of the turret and hull dynamics and the original Cadillac Gage stabilization system was generated for use in the determination of system parameters that could not be measured directly and for evaluating the original system with derived acceleration feedback and alternate stabilization schemes. This simulation verified the criticalness of the original system to parameter variations. The effectiveness of the differential pressure feedback scheme, which was originally suggested by A. J. Wroble of Cadillac Gage Company, was demonstrated by the simulation.

The differential pressure feedback scheme was evaluated in the field on the MICOM tank at a Redstone Arsenal range and on other tanks at the Chrysler range. The primary purpose of the performance tests on the MICOM tank was to demonstrate the hands-off performance of the new stabilization scheme. The

cross-country aim retention was evaluated by pivot steer and zig-zag maneuvers. The system tests at the Chrysler range showed that the new differential pressure feedback eliminated the requirement for individual tuning of each set of hardware since the system used with the MICOM tank was placed on other tanks and showed good performance without tuning. Bug-tracker tests performed on both the MICOM and Chrysler tanks with pressure feedback showed that the modified system would exceed the slow tracking requirements. System gains were varied during these evaluations, but the reason for this was to get an idea of the maximum allowable range of gain settings so that a fixed gain could be placed near the center of the allowable range.

This report describes the sensitivity analysis study performed on the turret azimuth modified stabilization system with differential pressure feedback. Both unit-to-unit and environmental variations in tank and stabilization system parameters were considered. The reasoning behind the magnitudes of the errors is discussed and it is obvious from this discussion that most of these values are obtained primarily through engineering judgement. Fortunately, very few of the parameter variations are found to have any significant effect on system performance and those that do have a significant effect have statistics that can be defended to some degree.

The most meaningful portion of the sensitivity analysis is the Cross-Country Aim Retention or pivot steer evaluation, because this is the only hands-off performance specification given in the requirements.[1]

The other criteria involve the man-in-the-loop so that the simulation could only approximate the conditions of the actual acceptance tests since a model of the operator was not included. In addition, the assumptions upon which the simulation was based and the way that tank parameters were measured made it most accurate in the study of pivot steer performance.

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[1] Performance Requirements for Turret, Cupola, and Gun Control System, U. S. Army Tank Automotive Center, Warren, Michigan, 17 February 1966, Report No. 11608400 (Unclassified).

Section II. PERFORMANCE CRITERIA FOR SENSITIVITY ANALYSIS

The MICOM pressure feedback scheme for improving the turret traverse accuracy and stability was evaluated to find its sensitivity to variations in vehicle physical and control system parameters. These parameter variations were assumed to be caused by tank and control system unit-to-unit differences and by environmental extremes.

Representative specifications[2] covering the overall performance range of the stabilization system which were chosen for evaluation were:

a) Cross-Country Point of Aim Retention

b) Gun Laying on Stationary Target, Vehicle Stationary

c) Gun Laying on Moving Target, Vehicle Stationary.

The first specification is a measure of the stabilization system hands-off accuracy under transient and steady-state conditions. The high-speed performance and transient response of the turret system is demonstrated by specification b). The last specification is a measure of the turret tracking accuracy and smoothness. A detailed disucssion of the applicability of these specifications and their use in the sensitivity analysis follows.

1. Cross-Country Point of Aim Retention

In order to have a repeatable measure of cross-country aim retention, the performance requirements for the turret traverse stabilization system specify a pivot steer maneuver in place of actual cross-country tests. For this test the tank is to pivot 180 degrees in not more than 8 seconds. The main gun and sights are to remain within 2 mils of the original aimpoint during the pivot steer, and to return to within 1 mil of the original aimpoint at the completion of the pivot steer

The MICOM simulation of the turret and hull motion in the horizontal plane gives an accurate representation of pivot steer performance. The hull rate for the simulation is matched to the hull rate that was measured on the MICOM tank during pivot steer maneuvers.

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[2] Ibid.

2. Gun Laying on Sationary Target, Vehicle Stationary

A lay-off of 90 degrees was chosen for evaluation of the MICOM modified system. The performance specification allows 9.5 seconds to position the gunsight on a 0.25-mil target from this turret lay-off position. An exact representation of this requirement could not be mechanized since the gunner is in the loop and greatly influences the positioning time by his method of accelerating and decelerating the turret.

For the simulation it was assumed that the maximum turret rate was commanded for 3 seconds and then the control handles released. This procedure does not give a turret position change of exactly 90 degrees, but it does indicate the effects of parameter changes on the turret transient response. It was assumed that if the turret position change was greater than 90 degrees in a time significantly less than 9.5 seconds the gunner should be able to lay-on a target within the prescribed time interval.

3. Gun Laying on Moving Target, Vehicle Stationary

This test is a measure of smoothness of tracking and response of the turret stabilization system. However, the response cannot be accurately evaluated without a knowledge of the type of inputs that the gunner will introduce into the system to get the gunsight onto the target. For slow tracking rates the gunner must get the control system out of the deadband created by servovalve third stage overlap before the turret will track. Therefore, for the sensitivity analysis it was assumed that the turret is tracking at the desired rate at the beginning of the time interval of interest.

A tracking rate of 0.25 mil per second was chosen for the sensitivity analysis. This rate was chosen since it appeared from experience on several tanks that this slow-speed tracking was the most likely to be affected by tracking roughness. The analysis was accomplished by integrating turret rate and adding the integrated target rate to an integrated target rate. The difference between these two integrated rates was taken to be the amount that the line-of-sight was off of the center of the target. In order to satisfy system requirements. this line-of-sight error must be no greater than ±0.125 mil.

Section III. ERROR MAGNITUDES FOR ANALYSIS

Gaussian distributions of error sources were assumed. Thus, the standard deviation of the error source used for the sensitivity analysis was the root-sum-square of unit-to-unit and environmental variations. In most instances both variations were determined by an educated estimation; however, as shown in a subsequent section, only one error source had a significant effect on system performance and the magnitude of this source can be substantiated with relatively high confidence.

The reasons behind the error magnitudes chosen for the analysis follow. The determination of the nominal values of these parameters is covered in an earlier report.[3]

1. Turret and Hull Moments of Inertia (J_t and J_h)

Unit-to-unit and loaded versus unloaded turret variations would probably not cause more than a 15-percent change in turret and hull moments of inertia about a bias value. The bias value would be the median of the loaded and unloaded moments of inertia. Thus the standard deviation of turret or hull moment of inertia was taken to be 5 percent of the bias value of the respective quantity.

2. Geartrain Moment of Inertia (J_e)

Since the reflected geartrain inertia is the dominant portion of geartrain plus hydraulic motor rotating member moment of inertia, the specified maximum variation in this value is assumed for the complete quantity. It is assumed that the maximum tolerance of 20 percent is a 3-sigma value. Therefore, the standard deviation is taken to be 7 percent of the nominal geartrain plus motor rotating member moment of inertia.

3. Suspension Spring and Damper (K_h and B_h)

These quantities were obtained by assuming a simplified model of the vehicle suspension and then adjusting the model parameters to give a match to test data from the MICOM tank. Due to the uncertainty in this procedure, the

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[3] Wetheral, T. G., Jordan, W. E., and Clayton, B. J., M60A1E2 Turret Stabilization System Analysis Phase I Interim Report, U. S. Army Missile Command, Redstone Arsenal, Alabama, August 1969, Un-numbered draft report, (Unclassified).

standard deviation of each of these quantities was assumed to be 10 percent of the value obtained by matching.

4. Fluid Compliance (K_f)

The nominal bulk modulus of the hydraulic fluid was taken to be 150,000 pounds per square inch. The maximum unit-to-unit variation was taken to be 30 percent of the nominal value and includes the effects of variations in the amount of air trapped in the fluid. It was estimated that the bulk modulus would not vary more than 50 percent of the nominal value under environmental extremes. Therefore the standard deviation of the bulk modulus was taken to be 20 percent of the nominal value and includes both unit-to-unit and environmental effects. The fluid compliance was taken to be a constant function of bulk modulus and therefore had a standard deviation of 20 percent of its nominal value.

5. Geartrain Structural Spring and Damper (K_g and B_g)

The structural springiness of the geartrain should have a relatively small unit-to-unit variation. However, the spring constant was obtained by matching simulator results to test results from the MICOM tank. For this reason an uncertainty standard deviation of 10 percent of the nominal value was assumed.

The effect of geartrain viscous damping was so small in comparison to the geartrain coulomb friction that variations in this quantity were not considered.

6. Ammunition Basket Spring and Damper (K_B and B_B)

The parameters of the assumed ammunition basket suspension model were the original Cadillac Gage values which gave a reasonable match between simulation and test data. Since the confidence in the model parameters was not too high, a standard deviation of 10 percent of the respective values was assumed.

7. Turret-to-Hull and Geartrain-to-Turret Coulomb Friction (B_c and B_{cg})

Breakaway and running torque measurements were made on three tanks by Chrysler and on one tank by MICOM. From these four vehicles the standard deviation of the sum of turret-to-hull and the reflected geartrain-to-turret coulomb friction was found to be approximately 20 percent of the mean value. Both the breakaway and running friction measurements were used in

calculating this standard deviation since the slow running friction was found to be essentially the same as the breakaway friction. It was assumed that environmental extremes would cause less than a 10 percent variation from the nominal value of coulomb friction; therefore a standard deviation of 20.5 percent of the nominal value was taken to represent both unit-to-unit and environmental effects.

8. Turret-to-Hull Viscous Friction (B)

Due to the magnitude of the turret-to-hull coulomb friction, it was not possible to measure the turret-to-hull viscous friction. Therefore, the value determined by Cadillac Gage was used. The standard deviation of this value was taken to be 10 percent of the nominal. In addition, it was assumed that the maximum environmental variation was 10 percent of the nominal value giving a total standard deviation of 10.5 percent.

9. Differential Pressure Feedback Gain ($K_{\Delta P}$)

It was assumed that this gain should have a standard deviation no greater than 10 percent of the nominal value.

10. Servovalve Gain, Natural Frequency, and Damping

It was assumed that the gain of the servovalve would always be within 10 percent of the nominal value giving a standard deviation of approximately 3 percent of nominal.

The servovalve natural frequency is supposed to be between 80 and 90 hertz for any unit under the tank environmental limits. However, test results from the MICOM tank indicate that the natural frequency is somewhat lower than this range. Therefore, the standard deviation of servovalve natural frequency was taken to be 5 percent of the nominal value.

The standard deviation of the servovalve damping ratio was taken to be 7 percent of the nominal. This includes both unit-to-unit and environmental variations.

11. Gyro Natural Frequency, Damping, and Scale Factor

The gyro natural frequency standard deviation was taken to be 7 percent of the nominal value.

The standard deviation of gyro damping ratio was taken to be 10 percent of the nominal damping ratio. There was some question as to the range of damping ratio that would be considered since at -54°C the ratio can be as much as 233 percent below the nominal value. However, it was not considered likely that the ambient temperature would approach this low value when the tank had been operated for a short time.

The standard deviation of the gyro scale factor is taken to be 10 percent of the nominal scale factor. This error source includes the variation in gain between the gyro output and the demodulator output which was found to have a standard deviation of approximately 8 percent of the nominal value for the circuit boards whose gain was measured at MICOM. The gyro specifications state that the gyro scale factor can be as much as 17 percent different from the nominal value over the temperature range of -65° to +165°F. The maximum environmental deviation was taken to be ±8.5 percent of nominal which would correspond to a more reasonable temperature range of 0° to +120°F if the percent variation to temperature relationship is linear. In addition, the gyro output for any input rate can depart from nominal scale factor, which is a best-fit straight line, by as much as a voltage corresponding to 0.3 degree per second plus 0.5 percent of the nominal output. Consideration of all these errors indicates that a 1-sigma value of 10 percent is reasonable.

12. Hull Sync Gain (K_{HS})

The standard deviation of the hull sync gain was taken to be 5 percent of the nominal value. The variations in this value are due to setting inaccuracy and gain changes in the LVDT, amplifiers, and demodulator under environmental extremes. The setup procedure for this gain will eliminate unit-to-unit variations in LVDT, amplifier, and demodulator gains.

13. Third Stage Valve Overlap

The overlap required to match simulator to tank test results was 133 percent above the specified value of overlap. For this reason the standard deviation of valve overlap was taken to be 50 percent of the specified value.

14. Traverse Motor Stall Torque and Gain Constant (T_s and K)

Since the stall torque of the traverse motor in the MICOM tank was 10.5 percent below the nominal value, it was assumed that the stall torque standard deviation could be as much as 5 percent of the nominal value. This value also includes the variations in regulated supply pressure.

The data utilized in the derivation of the hydraulic gain constant for the MICOM tank indicated that, for that tank, the standard deviation of hydraulic gain constant was approximately 3 percent of the nominal value. The standard deviation for all tanks was assumed to be 5 percent of the nominal value.

Section IV. RESULTS OF SENSITIVITY ANALYSIS

1. System Gains for Sensitivity Analysis

a. Position Gain

For the sensitivity analysis the position gain corresponded to a POS potentiometer setting of 0.5; integrator gain of 106; and summing amplifier input resistor of 250 kilohms. This results in a gain of $K_P = 654$ milliamperes per radian or $K'_P \simeq 41$. By way of comparison, the highest value of position gain that could be set on the MICOM tank with the original derived acceleration feedback was $K_P = 219$ milliamperes per radian. On the MICOM tank it was possible to increase the position gain more than three times greater than the value chosen for this sensitivity analysis, but there was not sufficient testing performed on other tanks to insure that they would operate reliably with this high gain. The specified value was chosen as a compromise between accuracy and reliable operation for all test conditions.

b. Velocity Gain

The velocity gain was set at $K_V = 27.7$ milliamperes per radian per second or $K'_V \simeq 1.73$. This corresponds to VEL potentiometer setting of 0.5 and a summing amplifier input resistor of 56 kilohms.

This gain appears to have no significant effect on turret hangoff error or tracking smoothness. Its primary effect is on the number of overshoots of turret turning rate when large rates are commanded.

c. Hull Sync Gain

The hull sync gain was taken to be $K_{HS} = 81$ milliamperes per inch for the sensitivity analysis. This gain is obtained by the HULL SYNC potentiometer to give a hull channel demodulator output corresponding to 20.25 milliamperes when the third stage spool is at one end of its travel of 0.25 inch.

d. Pressure Feedback Gain

A pressure feedback gain of $K_{\Delta P}$ = 0.001 milliamperes per psid is toward the center of the range of values of $K_{\Delta P}$ which result in rough, slow-speed tracking on the high end and instability on the low end.

2. Cross-Country Point of Aim Retention (Pivot Steer)

The turret hangoff error during a 180-degree pivot steer in 8 seconds is shown in Figure 1 for all parameters nominal. It is noted that the turret error is greater than the specifiel 2-mil maximum for approximately 0.3 second during the pivot steer. After the maneuver, it is seen that the turret pointing error is greater than the 1-mil specification value for about 0.1 second. The drift exhibited during this maneuver was due partially to computer errors and partially to crosscoupling between hull and reference gyro channels as discussed in the Systems Analysis Report.[1] In the actual tank most of this drift is taken out via the bias control.

The degradation of pivot steer performance due to parameter variations is summarized in Table I. In order to make the effects of some of the errors large enough to measure, 2-sigma values of the parameter variations were used for all parameters in the study. It is seen from the data of this table that only hull gyro scale factor, hull sync gain, and traverse motor gain and stall torque variations have any significant effect on the maximum turret hangoff error or the time duration that the error is out of the specified maximum limit. Of these, the hull gyro scale factor causes by far the most error.

Figure 2 shows the turret hangoff error for both plus and minus 2-sigma variations in hull gyro scale factor for a counterclockwise pivot steer. It is noted that a high value of scale factor actually improves the pivot steer performance, while a low value of scale factor causes the hangoff error to be slightly out of tolerance during the complete pivot steer maneuver. It should be remembered that this error source includes the hull gyro scale factor variation and all the variations in gain between hull gyro and the summing amplifier.

3. Gun Laying on Stationary Target, Vehicle Stationary

The turret rate and turret angle for the simulated lay-on-target maneuver are shown in Figures 3 and 4. Only turret moment of inertia, gear-

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[4] Ibid.

TABLE I. EFFECT OF PARAMETER VARIATIONS ON PIVOT STEER PERFORMANCE

Parameter	Nominal Value	2σ Variation Percent of Nominal	Peak Error During Pivot Steer		Error At End of Pivot Steer		Peak Error After Pivot Steer		Steady-State Error After Pivot Steer		Max Time Out of Spec During Pivot Steer		Max Time Out of Spec After Pivot Steer	
			$+2\sigma$ (mils)	-2σ (mils)	$+2\sigma$ (mils)	-2σ (mils)	$+2\sigma$ (mils)	-2σ (mils)	$+2\sigma$ (mils)	-2σ (mils)	$+2\sigma$ (sec)	-2σ (sec)	$+2\sigma$ (sec)	-2σ (sec)
Nominal			2.6		0.4		-1.2		-0.4		0.3		0.1	
J_t	1.8×10^4	10	2.6	2.6	0.4	0.4	-1.2	-1.2	-0.4	-0.4	0.3	0.3	0.1	0.1
J_h	13.9×10^4	10	2.6	2.6	0.4	0.4	-1.2	-1.2	-0.4	-0.4	0.3	0.3	0.1	0.1
J_e	44[illegible]	14	2.7	2.7	0.3	0.4	-1.2	-1.2	-0.4	-0.8	0.3	0.4	0.1	0.2
K_h	7×10^7	20	2.6	2.6	0.3	0.3	-1.2	-1.2	-0.4	-0.4	0.3	0.3	0.1	0.1
K_f	27.1×10^6	40	2.6	2.7	0.4	0.4	-1.2	-1.2	-0.4	-0.4	0.3	0.3	0.1	0.1
K_g	4×10^6	20	2.6	2.6	0.4	0.4	-1.2	-1.2	-0.4	-0.4	0.3	0.3	0.1	0.1
K_B	3.8×10^6	20	2.8	2.6	0.3	0.3	-1.2	-1.2	-0.4	-0.4	0.3	0.3	0.1	0.1
B_H	6×10^5	20	2.6	2.6	0.3	0.3	-1.2	[illegible]	-0.4	-0.4	0.3	0.3	0.1	0.1
B	200	21	2.7	2.8	0.5	0.4	-1.0	-1.2	-0.2	-0.4	0.3	0.3	0.1	0.1
B_e	200	41	2.7	2.5	0.4	0.3	-1.2	-1.2	-0.4	-0.4	0.3	0.3	0.1	0.1
B_g	7.9×10^{-2}	0	-	-	-	-	-	-	-	-	-	-	-	-
B_{cg}	410	41	2.8	2.4	0.4	0.2	-1.2	-1.2	-0.4	-0.3	0.3	0.2	0.1	0.1
B_B	1.23×10^5	20	2.6	2.6	0.4	0.4	-1.1	-1.1	-0.4	-0.3	0.3	0.3	0.1	0.1
$K_{\Delta P}$	1×10^{-3}	10	2.8	2.8	0.4	0.4	-1.1	-1.1	-0.4	-0.4	0.3	0.3	0.1	0.1
S/V ω_n	313	10	2.8	2.6	0.4	0.4	-1.1	-1.2	-0.4	-0.4	0.3	0.3	0.1	0.1
S/V δ	0.8	14	2.6	2.6	0.4	0.4	-1.1	-1.1	-0.4	-0.4	0.3	0.3	0.1	0.1
MRG ω_n	184	4	2.7	2.6	0.4	0.4	-1.1	-1.1	-0.2	-0.2	0.3	0.3	0.1	0.1
MRG δ	0.75	20	2.[illegible]	2.8	0.45	0.4	-1.1	-1.1	-0.2	-0.2	0.3	0.3	0.1	0.1
MRG s/f	0.1	20	2.3	3.1	0.3	0.5	-1.1	-1.3	-0.4	-0.4	0.3	0.4	0.1	0.2
HG ω_n	184	4	2.6	2.6	0.4	0.4	-1.0	-1.1	-0.2	-0.2	0.3	0.3	0.1	0.1
HG δ	0.75	20	2.7	2.6	0.4	0.4	-1.2	-1.1	-0.2	-0.3	0.3	0.3	0.1	0.1
HG s/f	0.1	20	-2.5	4.9	-1.6	2.3	-2.2	-1.1	-0.6	-0.6	0.3	7.7	0.3	0.1
K_{hyd}	2.35	6	2.6	2.8	0.4	0.4	-1.2	-1.2	-0.3	-0.4	0.3	0.3	0.1	0.1
K	0.065	10	1.7	3.9	-0.3	1.1	-1.2	-1.4	-0.1	-0.8	0.0	0.9	0.1	0.2
K_{HS}	81	10	3.7	1.7	1.4	-0.8	-1.0	-1.6	-0.4	-0.4	0.5	0.0	0.0	0.2
Overlap	2.33×10^{-3}	50	2.8	2.5	0.4	0.3	-1.2	-1.2	-0.3	-0.4	0.4	0.3	0.1	0.2
T_s	6760	10	2	0.5	0	0.8	-1.2	-1.3	-0.2	-0.5	0	0.7	0.1	0.2

train equivalent moment of inertia, fluid compliance, coulomb friction, and traverse motor gain and stall torque caused a measureable effect on the peak value of turret velocity, maximum turret excursion, or the turret settling time. Of these only the turret moment of inertia and traverse motor gain and stall torque were significant.

Comparison is made in Table II between peak velocity, final angle, and settling time of the turret for the cases of all parameters nominal and for the most significant error sources. These data give no indication that meeting the time requirement of 9.5 seconds to lay on a target displaced by 90 degrees would be impossible for any parameter variation.

TABLE II. EFFECT OF MOST CRITICAL PARAMETER VARIATIONS ON TURRET ANGULAR RESPONSE

Parameter	Peak Turret Velocity		Final Turret Angle		Turret Settling Time	
	$+2\sigma$ deg/sec	-2σ deg/sec	$+2\sigma$ degrees	-2σ degrees	$+2\sigma$ sec	-2σ sec
Nominal	44.1		110.6		7	
J_t	41.8	47.6	103.1	120.3	7.6	6.8
K'	45.8	42.4	112.9	104.3	7	7
T_s	48.7	40.1	121.5	98.6	7	7

4. Gun Laying on Moving Target, Vehicle Stationary

There was no noticeable change in slow-speed tracking smoothness for any of the parameter variations used for this sensitivity analysis. For some runs tracking roughness would be demonstrated, but it was not of sufficient magnitude to pull the gun off of a 0.25-mil target and could not be related to any particular error sources. The tracking roughness would occur during random runs even for the condition of all parameters at their nominal value.

Section V. CONCLUSIONS

The sensitivity analysis of the M60A1E2 turret traverse stabilization and control system demonstrated that the MICOM pressure feedback scheme is effective in overcoming the dynamic accuracy problems of the original system with derived acceleration feedback. In addition, the improved system exhibits a very low sensitivity to system parameter variations so that changes in the physical properties of the system components due to either age or environment will not cause a major degradation in the performance of the stabilization and control system.

It was noted that by far the most serious degradation in cross-country aim retention was due to variations in hull gyro scale factor and the gain between hull gyro and the summing amplifier. Fortunately, this error source was one of few for which there were data available from manufacturers' specifications and test results so that there is a relatively high level of confidence in the statistics of the error source. Even though the error was slightly out of the specified bound, it was still much better than has been obtained with the original system.

There was no indication that any of the error sources would have prevented the turret traverse system from meeting the specified performance requirements for lay-on a target or tracking smoothness.

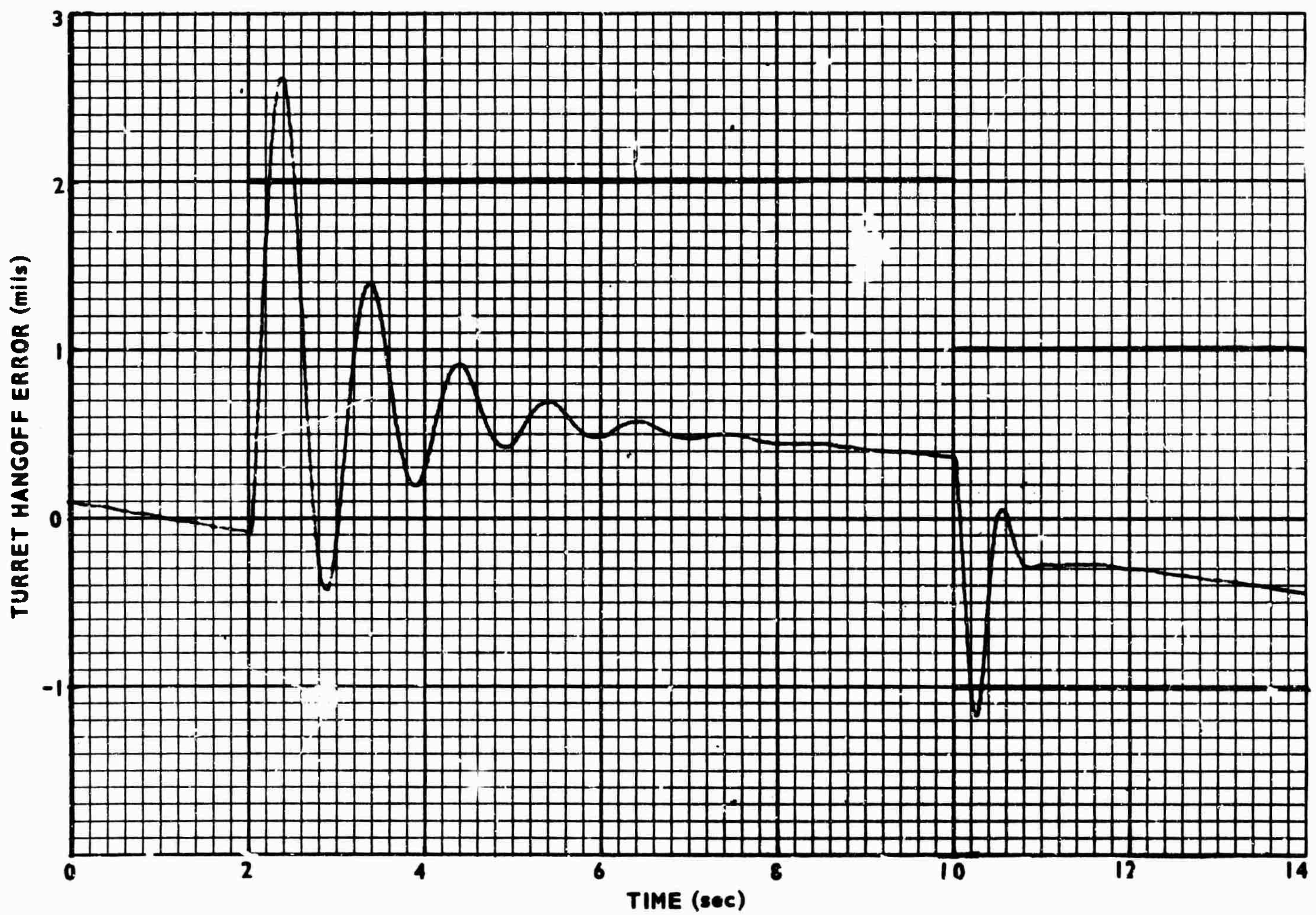

FIGURE 1. TURRET HANGOFF ERROR DURING PIVOT STEER, ALL PARAMETERS NOMINAL

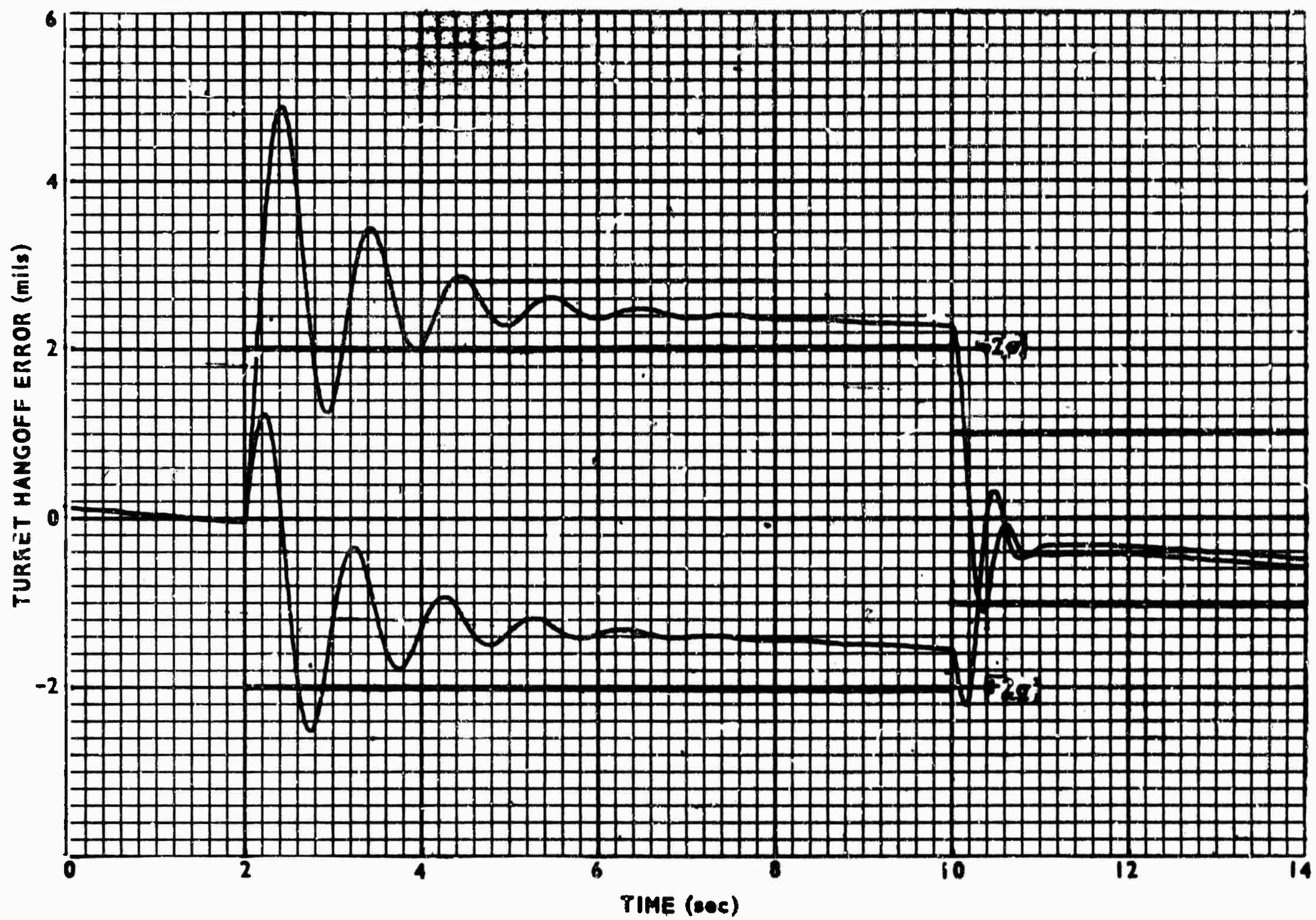

FIGURE 2. TURRET HANGOFF ERROR DURING PIVOT STEER, HULL GYRO SCALE FACTOR ERROR

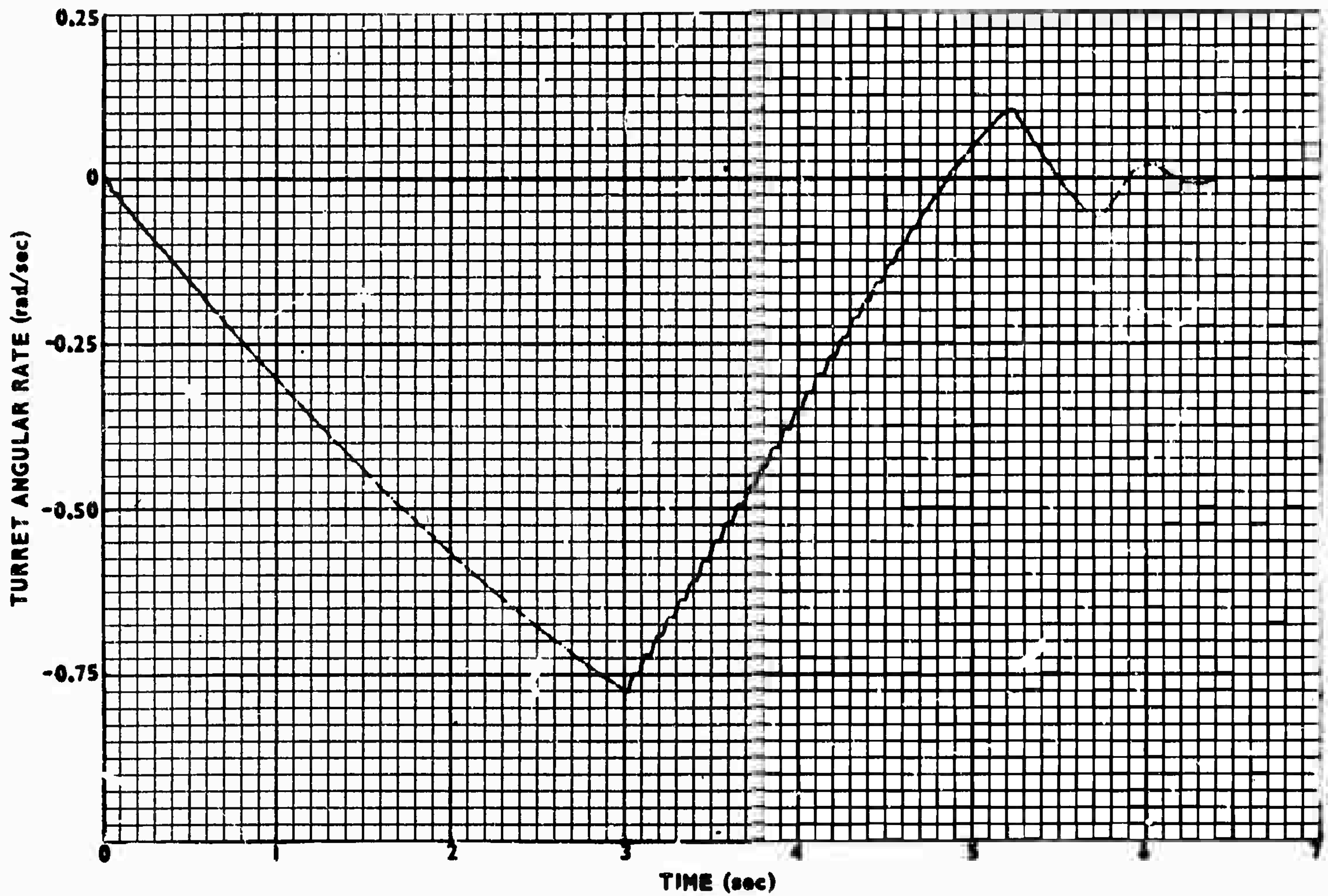

FIGURE 3. TURRET ANGULAR RATE FOR A 3-SECOND FULL HANDLE COMMAND, ALL PARAMETERS NOMINAL

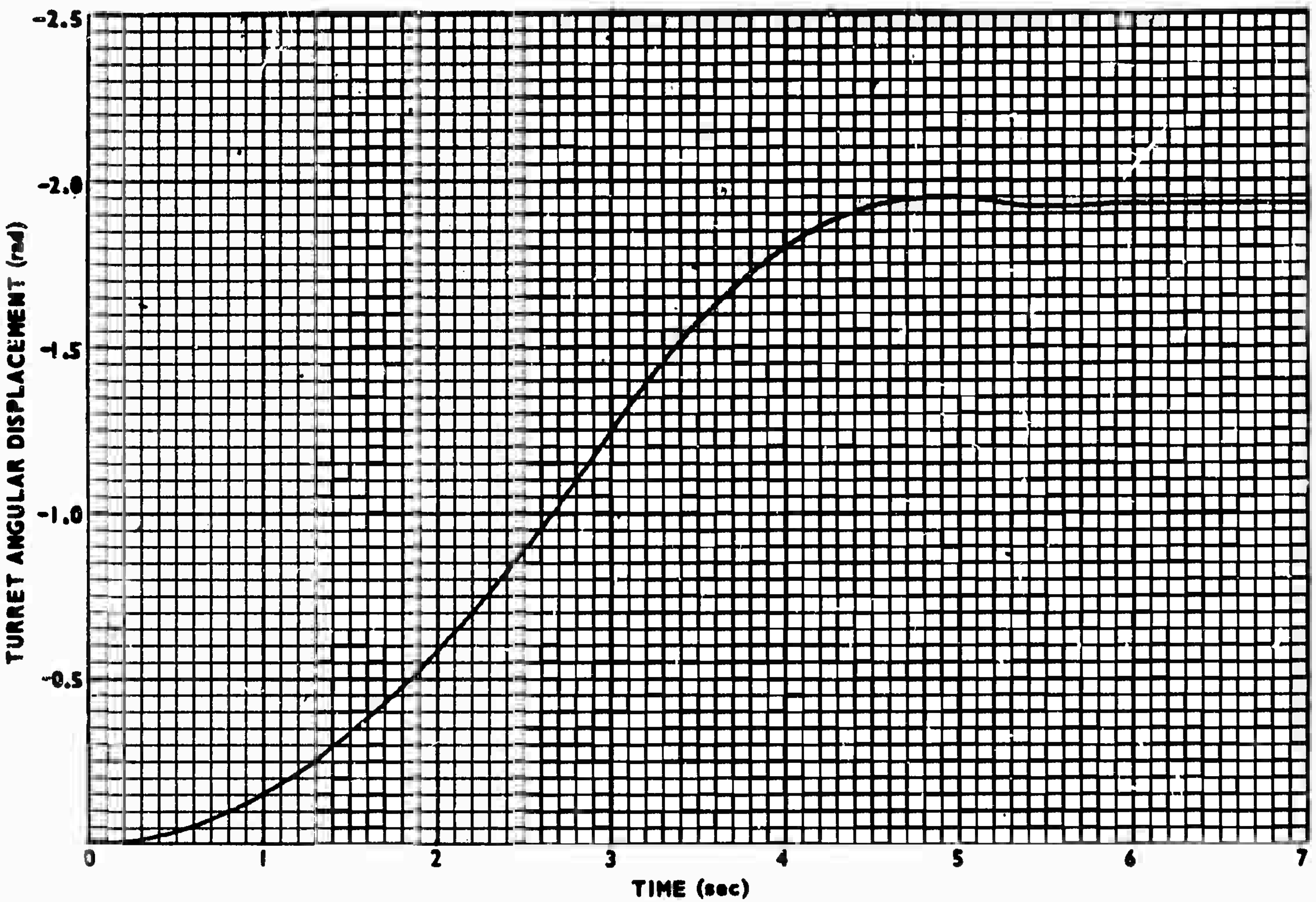

FIGURE 4. TURRET ANGULAR DISPLACEMENT FOR A 3-SECOND FULL HANDLE COMMAND, ALL PARAMETERS NOMINAL

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13. ABSTRACT

It has been demonstrated by performance evaluations on M60A1E2 tanks and by the results of simulator studies that the dynamic accuracy of the M60A1E2 turret azimuth stabilization system can be greatly improved with a minimum change in existing hardware. This change is the replacement of the derived acceleration compensation term in the control system by feedback of the differential pressure across the traverse motor. With this modification there is no longer a need to tune each stabilization system to an individual tank, and all control gains would be fixed prior to installation of the system into the tank.

A sensitivity analysis was performed on the modified stabilization system so that the effect of tank and stabilization system unit-to-unit and environmental parameter variations could be assessed. This study was performed with the aid of the analog simulation of the turret-hull azimuth model as determined by measurements taken on the MICOM tank. This report also describes the criteria used for evaluating stabilization system performance and the reasoning behind the statistics utilized to describe the parameter variations considered.

The sensitivity analysis showed that only one of the 27 error sources considered had a serious effect on the dynamic accuracy of the turret azimuth stabilization system. However, this error source, hull gyro channel gain, caused the turret hangoff during simulated cross-country aim retention to be only slightly out of the specification tolerance, and this error source has a much more degrading effect on the original system. There was no indication that any of the parameter variations would keep the turret azimuth stabilization system from meeting the

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ABSTRACT (Concluded)

specifications for laying on stationary and moving targets.

The modified system has demonstrated that it effectively overcomes the dynamic accuracy problems of the original system and is much less sensitive to parameter variations.